Sub-GeV atmospheric ν energy reconstruction in LArTPCs for DUNE

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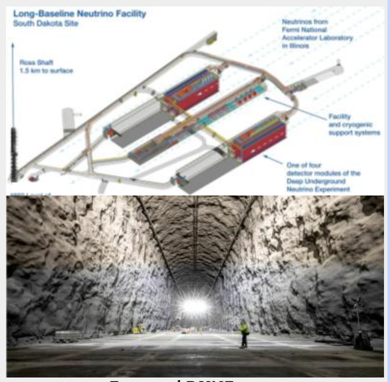
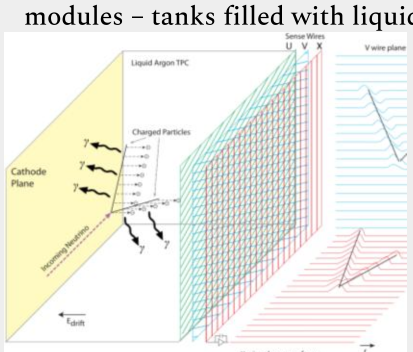
Introduction

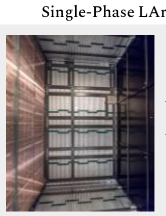
Neutrinos (ν) are weakly-interacting fundamental particles which oscillate between three 'flavors' – ν_e, ν_μ, ν_τ – as they travel. The extent of the 'mixing' between the three flavors and the rates at which they oscillate is determined by certain parameters – three mixing angles, the three neutrino mass differences, and more.


Excavated DUNE cavern

The next-generation neutrino experiment DUNE (Deep Underground Neutrino Experiment) will perform precise measurements of these neutrino oscillation parameters, including the unknown δ_{CP}: the difference in how neutrinos and antineutrinos ($\bar{\nu}$) oscillate (CP violation)[1]. To do so requires determining the energy E_ν of detected neutrinos. So, the DUNE Phase-II Far Detector (FD) will consist of four 17 kt Liquid Argon Time Projection Chamber (LArTPC) modules – tanks filled with liquid argon subjected to a uniform electric field.


Single-Phase LArTPC operating principle[2]

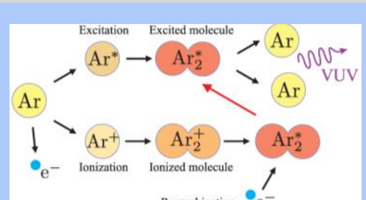
- When a ν interacts with an Ar nucleus in the tank, its E_ν is distributed among various emitted particles.
- The charged particles deposit their energy by ionizing and exciting Ar atoms along their path.
- The # of collected ionization e^- acts as a measurement of the amount of energy deposited by each particle, from which E_ν can be reconstructed.
- The same is true in principle for the # of scintillation γ, but low photodetector efficiency and coverage have so far made LArTPC light calorimetry infeasible, an issue which the design of the DUNE Phase-II FD aims to resolve. This would provide a second, independent method of estimating E_ν.[4]

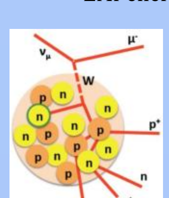

ProtoDUNE LArTPC[6]

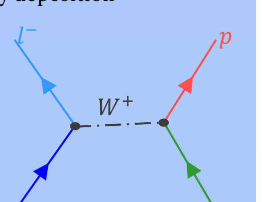
- Interactions between cosmic rays and particles in the upper atmosphere are a continuous source of ν with a wide range of E_ν spanning 0.1-100 GeV[3]. However, there is still much work to be done to improve reconstruction methods of ν events at the lower end of that energy range – sub-GeV events.

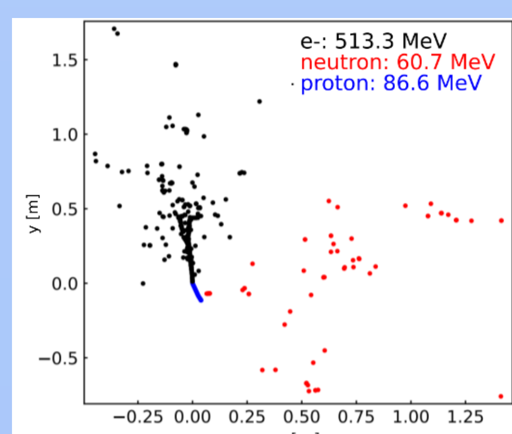
Research Goal

To characterize the performance of charge and light calorimetry in LArTPC in the reconstruction of sub-GeV incident ν energies, as well as explore avenues of ν / $\bar{\nu}$ discrimination.


LAr energy deposition[7]


Depiction of FSI[5]

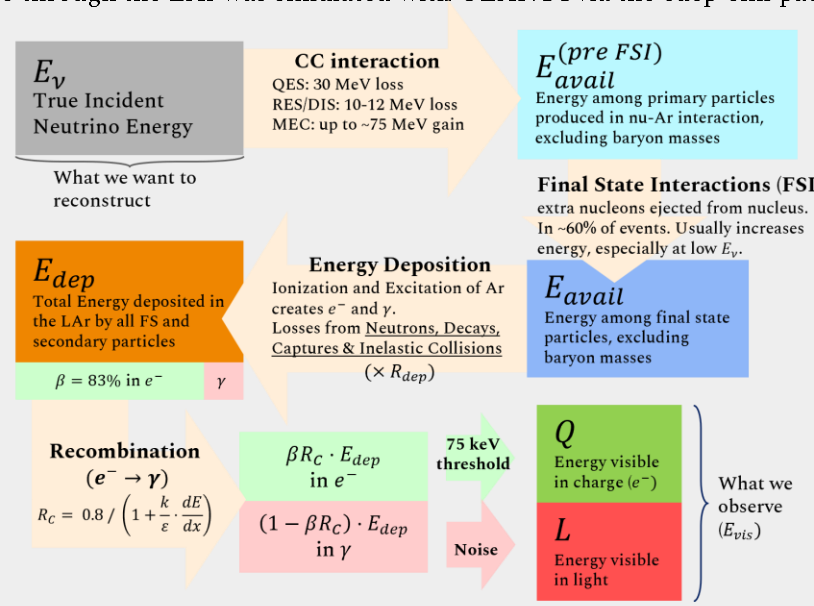

QES interaction

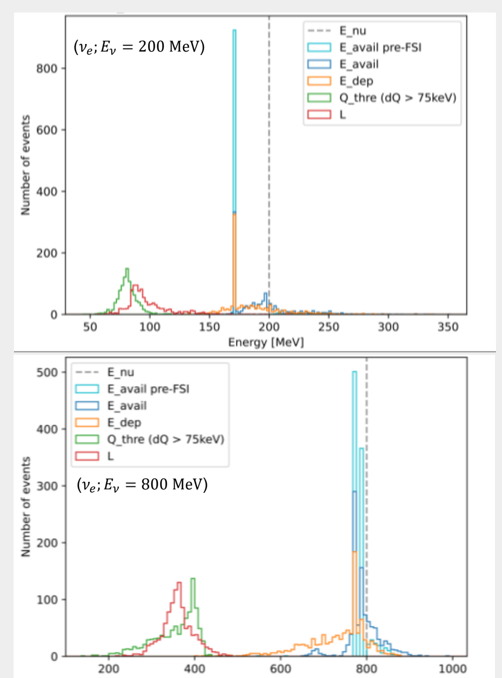


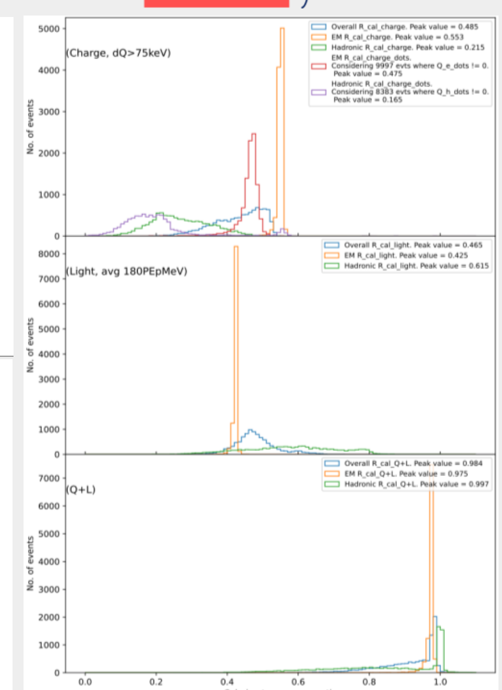
Event display of E_ν = 700 MeV QES event w/ FSI

Methods

The GENIE v3 Monte Carlo neutrino event generator was used to simulate 1000 ν_e-Ar and $\bar{\nu}_e$-Ar charged current interactions each for 10 different values of E_ν from 100 to 1000 MeV. The propogation of and energy deposition by the resultant particles through the LAr was simulated with GEANT4 via the edep-sim package.



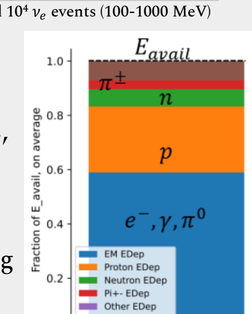

Distributions of E_{avail}, E_{dep}, Q, L for two sub-GeV ν_e event samples


Distributions of different R_{cal} for all 10^4 ν_e events (100-1000 MeV)

$$R_{cal} = \frac{E_{vis}}{E_{avail}} = \frac{E_{vis}}{E_{dep}} \cdot \frac{E_{dep}}{E_{avail}} = \begin{cases} \beta R_C \cdot R_{dep} & \text{(charge)} \\ (1 - \beta R_C) \cdot R_{dep} & \text{(light)} \end{cases}$$

Both R_C and R_{dep} vary for different particles at different energies, especially within the hadronic component, causing event-by-event fluctuation in R_{cal}.

Still, E_ν can be approximately reconstructed by dividing out the measured E_{vis} distribution by the peak value of the corresponding R_{cal} distribution – at least scaling the peak in E_{vis} to match the peak in E_{avail} – before adding back the constant ~30 MeV nucleon removal energy.



Breakdown of E_{avail} by FS particle for ν_e events

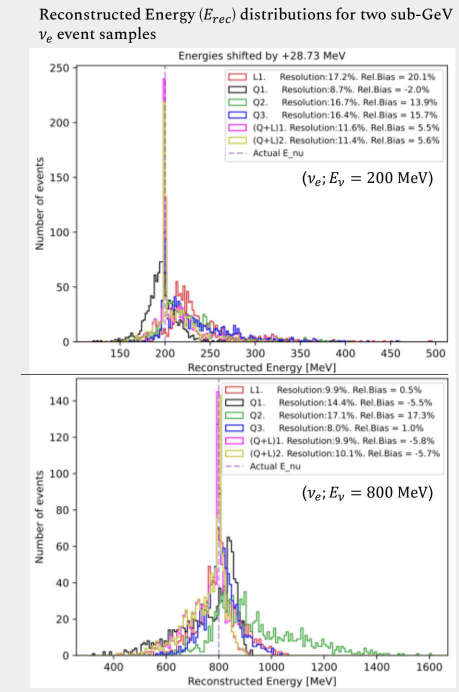
$$L1 = \frac{L}{R_{cal(\text{light})}} \qquad Q1 = \frac{Q}{R_{cal(\text{charge})}}$$

$$Q2 = \frac{Q_e}{R^e_{cal(\text{charge})}} + \frac{Q_h}{R^h_{cal(\text{charge})}} \qquad Q3 = E_{dep}^{\text{tracks}} + \frac{Q_e^{\text{dots}}}{R^{e,\text{dots}}_{cal(\text{charge})}} + \frac{Q_h^{\text{dots}}}{R^{h,\text{dots}}_{cal(\text{charge})}}$$

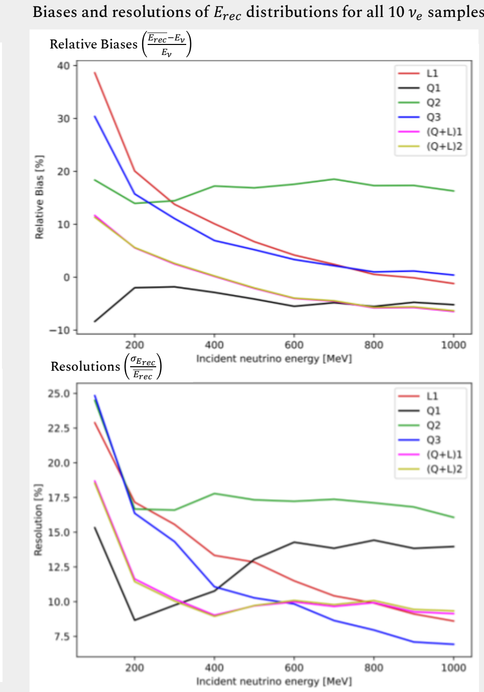
$$(Q+L)1 = \frac{Q+L}{R_{cal(\text{overall})}} \qquad (Q+L)2 = \frac{Q_e+L_e}{R^e_{cal(\text{overall})}} + \frac{Q_h+L_h}{R^h_{cal(\text{overall})}}$$

Results

Reconstructed Energy (E_{rec}) distributions for two sub-GeV ν_e event samples



Biases and resolutions of E_{rec} distributions for all 10 ν_e samples



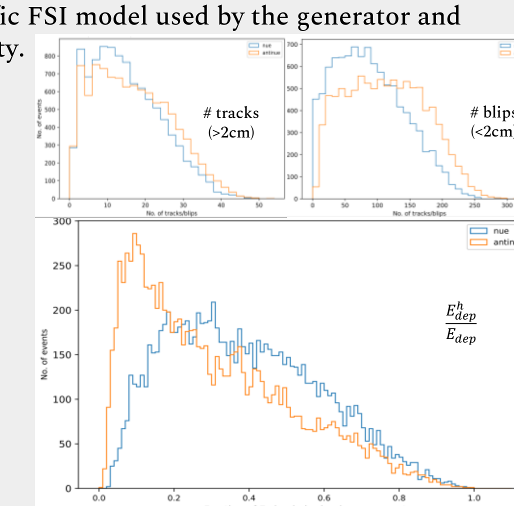
Future Work

Measuring the degree of CP violation in neutrino oscillation (δ_{CP}) requires being able to discriminate between ν and $\bar{\nu}$ in the detector. Specifically, achieving ν_e / $\bar{\nu}_e$ separation would provide the strongest δ_{CP} resolving power.

Comparing the frequencies of various event topologies among the generated 10^4 ν_e and $\bar{\nu}_e$ events reveals significant differences, since the pre-FSI nucleon (surviving in ~30% of events) is always a proton if ν_e and a neutron if $\bar{\nu}_e$. However, this ignores systematics e.g. threshold effects which can obscure particle identification. More importantly, the statistics of different event topologies would depend heavily on the specific FSI model used by the generator and may not correspond well with reality.

FS topology	ν_e	$\bar{\nu}_e$
1p0n0π	2865	0
1pXn0π	2258	2571
0pXn0π	76	4028
π+ present	917	41
π- present	57	882

- No significant difference between track multiplicities in ν_e vs $\bar{\nu}_e$ events was found, likely since FSI produce extra protons and neutrons with about equal likelihood.
- While the 'blip' multiplicity distributions are more distinct, they still cannot provide any definitive separation.
- Separation based on the fraction of the visible energy in the hadronic system is another promising angle.



Comparing distributions of some variables over all 10^4 ν_e and $\bar{\nu}_e$ events

Acknowledgements

I would like to thank Dr. Riccio and Dr. Shi for all their mentorship and guidance on this project, as well as the Stony Brook REU program for the opportunity.

References

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[2] B. Abi et al 2020 JINST 15 T08010
[3] DUNE Collaboration. *Reconstruction of atmospheric neutrinos in DUNE's horizontal drift far detector module*
[4] Ning et al *Self-compensating light calorimetry with liquid argon time projection chamber for GeV neutrino physics*
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[6] W Kevin *Deep Underground Neutrino Experiment (DUNE): Prospective Physics Program and Status*
[7] B Vittorio *The ArDM project: A liquid argon TPC for dark matter detection*